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Photon-Photon and Photon-Hadron Interactions at Relativistic Heavy Ion Colliders

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In central collisions at relativistic heavy ion colliders like the Relativistic Heavy Ion Collider RHIC/Brookhaven and the Large Hadron Collider LHC (in its heavy ion mode) at CERN/Geneva, one aims at detecting a new form of hadronic matter — the Quark Gluon Plasma. We discuss here a complementary aspect of these collisions, the very peripheral ones. Due to coherence, there are strong electromagnetic fields of short duration in such collisions. They give rise to photon-photon and photon-nucleus collisions with high flux up to an invariant mass region hitherto unexplored experimentally. After a general survey photon-photon luminosities in relativistic heavy ion collisions are discussed. Then photon-photon physics at various $\gamma\gamma$-invariant mass scales is discussed. The region of several GeV, relevant for RHIC is dominated by QCD phenomena (meson and vector meson pair production). Invariant masses of up to about 100 GeV can be reached at LHC, and the potential for new physics is discussed. Lepton-pair production, especially electron-positron pair production is copious. Due to the strong fields there will be new phenomena, especially multiple e^+e^- pair production.

1 Introduction

Due to the coherent action of all the charges in the nucleus fast nuclei are strong sources of equivalent (or quasireal) photons. The virtuality of the photon is related to the size R of the nucleus by

$$Q^2 \lesssim 1/R^2, \tag{1}$$

the condition for coherence. The maximum energy of the quasireal photon is therefore given by

$$\omega_{max} \approx \frac{\gamma}{R}, \tag{2}$$

where γ is the Lorentz factor. We use natural units, setting $\hbar = c = 1$.

The collisions of e^+ and e^- has been the traditional way to study $\gamma\gamma$-collisions. Similarly photon-photon collisions can also be observed in hadron-hadron collisions. Since the photon number scales

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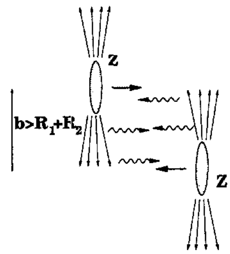

Figure 1: *Two fast moving electrically charged objects are an abundant source of (quasireal) photons. They can collide with each other and with the other nucleus. For peripheral collisions with impact parameters $b > 2R$, this is useful for photon-photon as well as photon-nucleus collisions.*

with Z^2 (Z being the charge number of the nucleus) such effects can be particularly large. Of course, the strong interaction of the two nuclei has to be taken into consideration.

The equivalent photon flux present in medium and high energy nuclear collisions is very high, and has found many useful applications in nuclear physics [1], nuclear astrophysics [2, 3], particle physics [4] (sometimes called the "Primakoff effect"), as well as, atomic physics [5]. With the construction of the "Relativistic Heavy Ion Collider" (RHIC) and the "Large Hadron Collider" (LHC) scheduled for 1999 and for 2004/2008, respectively, one will be able to investigate such collisions experimentally. The main purpose of these heavy ion colliders is the formation and detection of the quark-gluon-plasma in central collisions. The present interest is in the "very peripheral (distant) collisions", where the nuclei do not interact strongly with each other. From this point of view, grazing collisions and central collisions are considered as a background. It is needless to say that this "background" can also be interesting physics of its own.

The equivalent photon spectrum extends up to several GeV at RHIC energies ($\gamma \approx 100$) and up to about 100 GeV at LHC energies ($\gamma \approx 3000$), see Eq. (2). Therefore the range of invariant masses $M_{\gamma\gamma}$ at RHIC will be up to about the mass of the η_c, at LHC it will extend into an invariant mass range hitherto unexplored. Up to now hadron-hadron collisions have not been used for two-photon physics. An exception can be found in [6]. There the production of $\mu^+\mu^-$ pairs at the ISR was observed. The special class of events was selected, where no hadrons are seen associated with the muon pair in a large solid angle vertex detector. In this way one makes sure that the hadrons do not interact strongly with each other, i.e., one is dealing with peripheral collisions (with impact parameters $b > 2R$); the photon-photon collisions manifest themselves as "silent events". Dimuons with a very low sum of transverse momenta are also considered as a luminosity monitor for the ATLAS detector at LHC [7].

Experiments are planned at RHIC [8, 9, 10, 11, 12] and discussed at LHC [13, 14, 15]. We quote J.D.Bjorken [16]: *It is an important portion (of the FELIX program at LHC) to tag on Weizsaecker Williams photons (via the nonobservation of completely undissociated forward ions) in ion-ion running, creating a high luminosity $\gamma - \gamma$ collider.* Recent reviews are[17], [18], and [19].

2 From impact-parameter dependent equivalent photon spectra to $\gamma\gamma$-luminosities

Photon-photon collisions have been studied extensively at e^+e^- colliders. The theoretical framework is reviewed, e.g., in [20]. The basic graph for the two-photon process in ion-ion collisions is shown in Fig. 2. Two virtual (space-like) photons collide to form a final state f. In the equivalent photon approximation it is assumed that the square of the 4-momentum of the virtual photons is small, i.e., $q_1^2 \approx q_2^2 \approx 0$ and the photons can be treated as quasireal. In this case the $\gamma\gamma$-production is factorized into an elementary cross section for the process $\gamma + \gamma \to f$ (with real photons, i.e., $q^2 = 0$) and a $\gamma\gamma$-luminosity function. In contrast to the pointlike elementary electrons (positrons), nuclei are extended, strongly interacting objects with internal structure. This gives rise to modifications in the theoretical treatment of two photon processes. The virtual photons in relativistic heavy ion collisions can be treated as quasireal. This is a limitation as compared to e^+e^- collisions, where the two-photon processes can also be studied as a function of the corresponding masses q_1^2 and q_2^2 of the exchanged photon ("tagged mode").

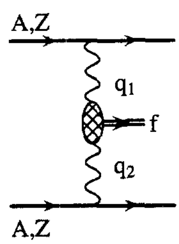

Figure 2: *The general Feynman diagram of photon-photon processes in heavy ion collisions: Two (virtual) photons fuse in a charged particle collision into a final system f.*

Relativistic heavy ions interact strongly when the impact parameter is smaller than the sum of the radii of the two nuclei. In such cases $\gamma\gamma$-processes are still present and are a background that has to be considered in central collisions [21, 22] . In order to study "clean" photon-photon events however, they have to be eliminated in the calculation of photon-photon luminosities as the particle production due to the strong interaction dominates. In the usual treatment of photon-photon processes in e^+e^- collisions plane waves are used and there is no direct information on the impact parameter. For heavy ion collisions on the other hand it is very appropriate to introduce impact parameter dependent equivalent photon numbers. They have been widely discussed in the literature (see, e.g., [1, 23, 24]). The cross section for a certain electromagnetic process is then

$$\sigma = \int \frac{d\omega}{\omega} n(\omega) \sigma_\gamma(\omega). \qquad (3)$$

A useful estimate is

$$n(\omega) \approx \frac{2Z^2\alpha}{\pi} \ln \frac{\gamma}{\omega R_{min}}. \tag{4}$$

The photon-photon production cross-section is obtained in a similar factorized form, by folding the corresponding equivalent photon spectra of the two colliding heavy ions [25, 26]

$$\sigma_c = \int \frac{d\omega_1}{\omega_1} \int \frac{d\omega_2}{\omega_2} F(\omega_1, \omega_2) \sigma_{\gamma\gamma}(W_{\gamma\gamma} = \sqrt{4\omega_1\omega_2}), \tag{5}$$

In Fig. 3 we give a comparison of effective $\gamma\gamma$ -luminosites (defined as collider luminosity times $\gamma\gamma$-luminosity) for various collider scenarios. We use the following collider parameters: LEP200: $E_{el} = 100\text{GeV}$, $L = 10^{32} cm^{-2} s^{-1}$, Pb-Pb heavy-ion mode at LHC: γ=2950, $L = 10^{26} cm^{-2} s^{-1}$, Ca-Ca: γ=3750, $L = 4 \times 10^{30} cm^{-2} s^{-1}$, p-p: γ=7450, $L = 10^{30} cm^{-2} s^{-1}$. In the Ca-Ca heavy ion mode, higher effective luminosities can be achieved as, e.g., in the Pb-Pb mode, since higher AA luminosities can be reached there. For further details see [27].

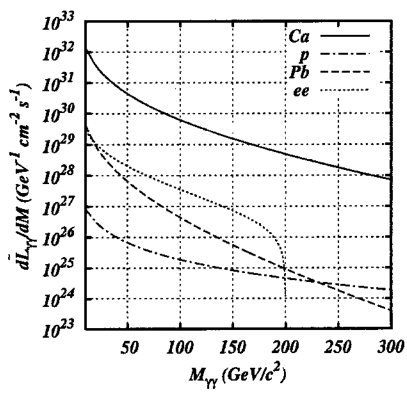

Figure 3: *Comparison of the effective $\gamma\gamma$-Luminosities ($L_{AA} \times L_{\gamma\gamma}$) for different ion species. For comparison the same quantity is shown also for LEP200.*

3 γ-A interactions

There are many interesting phenomena ranging from the excitation of discrete nuclear states, giant multipole resonances (especially the giant dipole resonance), quasideuteron absorption, nucleon resonance excitation to the nucleon continuum. Photo-induced processes lead in general to a change of the charge-to-mass ratio of the nuclei, and with their large cross section they are therefore a serious source of beam loss. Especially the cross section for the excitation of the giant dipole resonance, a collective mode of the nucleus, is rather large for the heavy systems (of the order of 100b). The cross section scales approximately with $Z^{10/3}$. Another serious source of beam loss is the e^+e^- bound-free pair creation. The contribution of the nucleon resonances (especially the Δ resonance) has also been confirmed experimentally in fixed target experiments with 60 and 200 GeV/A (heavy ions at CERN, "electromagnetic spallation") [28, 29, 30]. For details of these aspects, we refer the reader to [17, 31, 32, 33], where scaling laws, as well as detailed calculations for individual cases are given.

The interaction of quasireal photons with protons has been studied extensively at the electron-proton collider HERA (DESY, Hamburg), with $\sqrt{s} = 300$ GeV ($E_e = 27.5$ GeV and $E_p = 820$ GeV in the laboratory system). This is made possible by the large flux of quasi-real photons from the electron (positron) beam. The obtained γp center-of-mass energies (up to $W_{\gamma p} \approx 200$ GeV) are an order of magnitude larger than those reached by fixed target experiments. Similar and more detailed studies will be possible at the relativistic heavy ion colliders RHIC and LHC, due to the larger flux of quasireal photons from one of the colliding nuclei. Estimates of the order of magnitude of vector meson production in photon-nucleon processes at RHIC and LHC are given in [18]. At the LHC one can extend these processes to much higher invariant masses W. Whereas the J/Ψ production at HERA was measured up to invariant masses of $W \approx 160$ GeV, the energies at the LHC allow for studies up to ≈ 1 TeV.

At the LHC [14] hard diffractive vector meson photoproduction can be investigated especially well in AA collisions. In comparison to previous experiments, the very large photon luminosity should allow observation of processes with quite small γp cross sections, such as Υ-production. For more details see [14].

4 Photon-Photon Physics at various invariant mass scales

Up to now photon-photon scattering has been mainly studied at e^+e^- colliders. Many reviews [20, 37, 38] as well as conference reports [39, 40] exist. The traditional range of invariant masses has been the region of mesons, ranging from π^0 ($m_{\pi^0} = 135$ MeV) up to about η_c ($m_{\eta_c} = 2980$ MeV).

The cross section for $\gamma\gamma$-production in a heavy ion collision factorizes into a $\gamma\gamma$-luminosity function and a cross-section $\sigma_{\gamma\gamma}(W_{\gamma\gamma})$ for the reaction of the (quasi)real photons $\gamma\gamma \to f$, where f is any final state of interest. When the final state is a narrow resonance, the cross-section for its production in two-photon collisions is given by

$$\sigma_{\gamma\gamma\to R}(M^2) = 8\pi^2(2J_R+1)\Gamma_{\gamma\gamma}(R)\delta(M^2 - M_R^2)/M_R, \tag{6}$$

where J_R, M_R and $\Gamma_{\gamma\gamma}(R)$ are the spin, mass and two-photon width of the resonance R. This makes it easy to calculate the production cross-section $\sigma_{AA\to AA+R}$ of a particle in terms of its basic properties. We will now give a general discussion of possible photon-photon physics at relativistic heavy ion colliders. Invariant masses up to several GeV can be reached at RHIC and up to about 100 GeV at LHC. An interesting topic in itself is the e^+-e^- pair production. The fields are strong enough to produce multiple pairs in a single collisions. A discussion of this subjet together with calculations within the semiclassical approximation can be found in [34, 35, 36]

4.1 Basic QCD phenomena in $\gamma\gamma$-collisions

4.1.1 Light and heavy quark spectroscopy

One may say that photon-photon collisions provide an independent view of the meson and baryon spectroscopy. They provide powerful information on both the flavor and spin/angular momentum internal structure of the mesons. Much has already been done at e^+e^- colliders. Light quark spectroscopy is very well possible at RHIC, benefiting from the high $\gamma\gamma$-luminosities. Detailed feasibility studies exist [8, 9, 10, 11, 12]. In this study, $\gamma\gamma$ signals and backgrounds from grazing nuclear and beam gas collisions were simulated with both the FRITIOF and VENUS Monte Carlo codes. The narrow $p_\perp$-spectra of the $\gamma\gamma$-signals provide a good discrimination against the background. The possibilities of the LHC are given in the FELIX LoI [14].

The absence of meson production via $\gamma\gamma$-fusion is also of great interest for glueball search. The two-photon width of a resonance is a probe of the charge of its constituents, so the magnitude of the two-photon coupling can serve to distinguish quark dominated resonances from glue-dominated resonances ("glueballs"). In $\gamma\gamma$-collisions, a glueball can only be produced via the annihilation of a $q\bar{q}$ pair into a pair of gluons, whereas a normal $q\bar{q}$-meson can be produced directly. In a recent reference [42] results of the search for $f_J(2220)$ production in two-photon interactions were presented. There a very small upper limit for the product of $\Gamma_{\gamma\gamma}B_{K_sK_s}$ was given, where $B_{K_sK_s}$ denotes the branching fraction of its decay into K_sK_s. From this it was concluded that this is a strong evidence that the $f_J(2220)$ is a glueball.

For charmonium production, the two-photon width $\Gamma_{\gamma\gamma}$ of η_c (2960 MeV, $J^{PC} = 0^{-+}$) is known from experiment. But the two-photon widths of P-wave charmonium states have been measured with only modest accuracy. For RHIC the study of η_c is a real challenge [9]; the luminosities are falling and the branching ratios to experimental interest ing channels are small.

$C = -1$ vector mesons can be produced in principle by the fusion of three (or, less important, five, seven, ...) equivalent photons. The cross section scales with Z^6. It is smaller than the contributions discussed above, even for nuclei with large Z.

4.1.2 Vector-meson pair production. Total hadronic cross-section

There are various mechanisms to produce hadrons in photon-photon collisions. Photons can interact as point particles which produce quark-antiquark pairs (jets) , which subsequently hadronize. Often a quantum fluctuation transforms the photon into a vector meson (ρ,ω,ϕ, ...) (VMD component) opening up all the possibilities of hadronic interactions . In hard scattering, the structure of the photon can be resolved into quarks and gluons. Leaving a spectator jet, the quarks and gluon contained in the photon will take part in the interaction. It is of great interest to study the relative amounts of these components and their properties.

The L3 collaboration recently made a measurement of the total hadron cross-section for photon-photon collisions in the interval $5GeV < W_{\gamma\gamma} < 75GeV$ [41]. It was found that the $\gamma\gamma \rightarrow$hadrons cross-section is consistent with the universal Regge behavior of total hadronic cross-sections. The production of vector meson pairs can well be studied at RHIC with high statistics in the GeV region [8]. For the possibilities at LHC, we refer the reader to [14] and [15], where also experimental details and simulations are described.

4.2 $\gamma\gamma$-collisions as a tool for new physics

The high flux of photons at relativistic heavy ion colliders offers possibilities for the search of new physics. This includes the discovery of the Higgs-boson in the $\gamma\gamma$-production channel or new physics beyond the standard model, like supersymmetry or compositeness. While the $\gamma\gamma$ invariant masses, which will be reached at RHIC, will mainly be useful to explore QCD at lower energies, the $\gamma\gamma$ invariant mass range at LHC — up to about 100 GeV — will open up new possibilities.

A number of calculations have been made for a medium heavy standard model Higgs [43, 44, 45, 46]. For masses $m_H < 2m_{W^\pm}$ the Higgs bosons decays dominantly into $b\bar{b}$.Chances of finding the standard model Higgs in this case are marginal [18].

An alternative scenario with a light Higgs boson was, e.g., given in [47] in the framework of the "general two Higgs doublet model". Such a model allows for a very light particle in the few GeV region. With a mass of 10 GeV, the $\gamma\gamma$-width is about 0.1 keV. The authors of [47] proposed to look for such a light neutral Higgs boson at the proposed low energy $\gamma\gamma$-collider. We want to point out that the LHC Ca-Ca heavy ion mode would also be very suitable for such a search. In Refs. [48, 49] $\gamma\gamma$-processes at pp colliders (LHC) are studied. It is observed there that non-strongly interacting supersymmetric particles (sleptons, charginos, neutralinos, and charged Higgs bosons) are difficult to detect in hadronic collisions at the LHC. The Drell-Yan and gg-fusion mechanisms yield low production rates for such particles. Therefore the possibility of producing such particles in $\gamma\gamma$ interactions at hadron colliders is examined. Since photons can be emitted from protons which do not break up in the radiation process, clean events can be generated which should compensate for the small number. In [48] it was pointed out that at the high luminosity of $L = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at the LHC (pp), one expects about 16 minimum bias events per bunch crossing. Even the elastic $\gamma\gamma$ events will therefore not be free of hadronic debris.

Clean elastic events will be detectable at luminosities below $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This danger of "overlapping events" has also to be checked for the heavy ion runs, but it will be much reduced due to the lower luminosities.

5 Conclusion

Basic properties of electromagnetic processes in very peripheral hadron-hadron collisions are described. The method of equivalent photons is a well established tool to describe these kind of reactions. Reliable results of quasireal photon fluxes and $\gamma\gamma$-luminosities are available. Unlike electrons and positrons heavy ions and protons are particles with an internal structure. Effects arising from this structure are well under control. A problem, which is difficult to judge quantitatively at the moment, is the influence of strong interactions in grazing collisions, i.e., effects arising from the nuclear stratosphere and Pomeron interactions.

The high photon fluxes open up possibilities for photon-photon as well as photon-nucleus interaction studies up to energies hitherto unexplored at the forthcoming colliders RHIC and LHC. Interesting physics can be explored at the high invariant $\gamma\gamma$-masses, where detecting new particles could be within range. Also very interesting studies within the standard model, i.e., mainly QCD studies will be possible. This ranges from the study of the total $\gamma\gamma$-cross section into hadronic final states up to invariant masses of about 100 GeV to the spectroscopy of light and heavy mesons.

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